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THE (pP-P) TIME DIFFERENCE

31 March 1967

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Washington, D. C.

By

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THE (pP-P) TIME DIFFERENCE

SEISMIC DATA LABORATORY REPORT NO. 177

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ABSTRACT

An investigation to combine REMODE with velocity filtering over a three component array in order to enhance depth phases experienced considerable difficulty in aligning P and pP phases simultaneously. To explain this difficulty, seismograms from four earthquakes were analyzed at the 9 sites in the TFO Extended Array. The depth phase (pP) is well-defined on these seismograms. It is established that the time difference (pP-P) at the 9 stations of the array differs by as much as 0.5 seconds for the same earthquake. It is concluded that each phase P, pP, and in one case sP, has its own travel time anomalies for the TFO Extended Array. It is further concluded that REMODE should be applied to the three component seismograms, rather than to the sum of the horizontal and vertical components of the array.

1. THE (pP-P) TIME DIFFERENCE

There is a difference in the travel-time anomaly for P and pP at the TFO Extended Array. This difference is sufficient in some cases to result in near cancellation of pP if the seismograms are summed by aligning on P. On most seismograms it is not possible to determine the time of pP with sufficient accuracy to justify the above statement. If, however, the examples are limited to seismograms with well-defined pP, then the scatter of the time difference (pP-P) can be demonstrated.

Four groups of seismograms were selected from the vertical seismograms recorded at the TFO Extended Array for the following earthquakes:

Chile-Bolivia Earthquake - 16 April 1965
Peru Earthquake - 10 May 1965
N. Coast Chile Earthquake - 30 July 1965
Kurile Is. Earthquake - 18 May 1965

The time difference (pP-P) observed at the 9 stations of the TFO Extended Array for the above earthquakes were plotted on Figure 1 against Δ (surface distance). In each case the scatter of the points was about 0.5 seconds. The points were read by timing a well-defined peak or through, rather than attempting to read first motion.

The parametric lines in Figure 1 were plotted from the Jeffreys-Shimshoni Tables (Jeffreys and Shimshoni 1964). They establish a norm against which the slope and scatter of the pP-P times may be measured. The parametric values of h/R for values other than 0.00, 0.01 and 0.02 were interpolated from the tables.

As a result of using well-defined phases and selected earthquakes the times for both P and pP are believed to be correct with 0.1 second.

The Jeffreys-Bullen tables predict an increase in the time difference (pP-P) as a function of Δ (surface distance) and depth of focus measured by h/R, where h is hypocentral depth minus 33 km. and R is the earth's radius. This increase is measured by the slope of the h/R plots of Figure 1. It varies from 0.1 second for the Kurile Earthquake to slightly more than 0.2 seconds for the Chile-Bolivia Earthquake across the range of surface distances measured by the TFO Extended Array. The spread of surface distances, observed by the TFO array, is commonly 3^{o} to 4^{o}, varying with azimuth.

Figure 2 consists of reduced copies of a representative seismogram from each of the four earthquakes used in this study. As noted earlier, well-defined phases were used to determine the time difference (pP-P).

Tables 1 through 4 are the listings of the arrival times as determined from the 10 secs = 2 inches playbacks of the seismograms. Estimated reading accuracy is ± 0.1: as based on reading the times one day, setting the values aside, and making an independent reading the following day.

2. STATISTICAL ANALYSIS OF (pP-P) TIME DIFFERENCES

The visual evidence from the scatter of the plotted values of (pP-P) is clearly shown by Figure 1. In order to obtain a statistical measure of this scatter the following analysis was made. The relative smallness of the sample limits the conclusions to an indication of the confidence limits.

The mean and variances of the observed values of (pP-P) were computed using the standard formulas.

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

and

$$s_\chi^2 = \frac{1}{n-1} \sum_{i=1} (\chi_i - \bar{\chi})^2$$

The computed values are listed below.

	(pP-P)	s_χ^2
Kurile Eq. 18 May 1965	13.73	0.0451
N. Coast Chile Eq. 30 July 1965	18.20	0.0213
Peru Eq. 10 May 1965	26.38	0.0317
Chile-Bolivia Eq. 16 April 1965	31.32	0.0420

The 95% confidence intervals of the variance were estimated from the following formula

$$\frac{(n-1)\, s_\chi^2}{\chi^2 0.025} < \sigma^2 < \frac{(n-1)\, s_\chi^2}{\chi^2 0.975}$$

which resulted in the following data, for the four earthquakes analyzed:

Kurile Eq. - 18 May 1965

$0.0917 > \sigma^2 > 0.0114$

N. Coast Chile Eq. - 30 July 1965

$0.078 > \sigma^2 > 0.00914$

Peru Eq. - 10 May 1965

$0.116 > \sigma^2 > 0.0145$

Chile-Bolivia Eq. - 16 April 1965

$0.154 > \sigma^2 > 0.0194$

If the observed times for (pP-P) are all 0.1 second greater or less than the mean, the time differences of a pair becomes 0.2 seconds. The phase difference of a 1.0 sec period pulse is 1/5 x 360° or 72°. This would be sufficient phase difference to produce some distortion: however, the signal would probably be

recognizable. If this assumption is used as a basis for computation then

$$0.0367 > \sigma^2 > 0.00457$$

This is the 95% confidence region, for the assumption each time is 0.1 sec greater or less than the mean is the above range. This difference (72° for 1 sec period) can be thought of as a threshold. If the time differences are greater, say 0.2, then the phase shift is 144° and summing produces near cancellation. This criteria of cancellation is not readily established, since the pulses to be summed contain a range of frequencies. It is probable that for reinforcement to occur, when the pulses are summed, requires a narrower range of variance than the range computed for the 0.1 second assumption. In each case the actual 95% confidence interval is greater than that computed for the 0.1 sec. assumption.

3. CONCLUSIONS:

1. Travel time anomalies for pP phases are different than those for P by as much as 0.5 seconds over the TFO Extended Array.

2. Because of the different travel time anomalies, signals aligned on P will misalign pP and vice versa.

3. Other compressional phases can be expected to require still different travel-time anomalies. In fact, pP phases from sources at different depths can be expected to require different travel time anomalies.

4. The application of REMODE operators to the summation traces from three component, short period seismic arrays will be considerably less than optimum unless different array alignments are imposed at different times during the earthquake signal.

5. The false signal rate for REMODE processors, due to chance waveform on matchings in vertical and horizontal traces, will be as high for array summation traces as for single seismograms.

6. Array summing of REMODE outputs from three component sites will suffer the same phase misalignments as raw data.

Thus, the recommended technique for REMODE processing of three component arrays is to REMODE each three component site as a unit and then display the results as a suite of seismograms. Array mixing of all verticals separately and all horizontals separately first is not a promising method of enhancing the sensitivity of REMODE for depth phases.

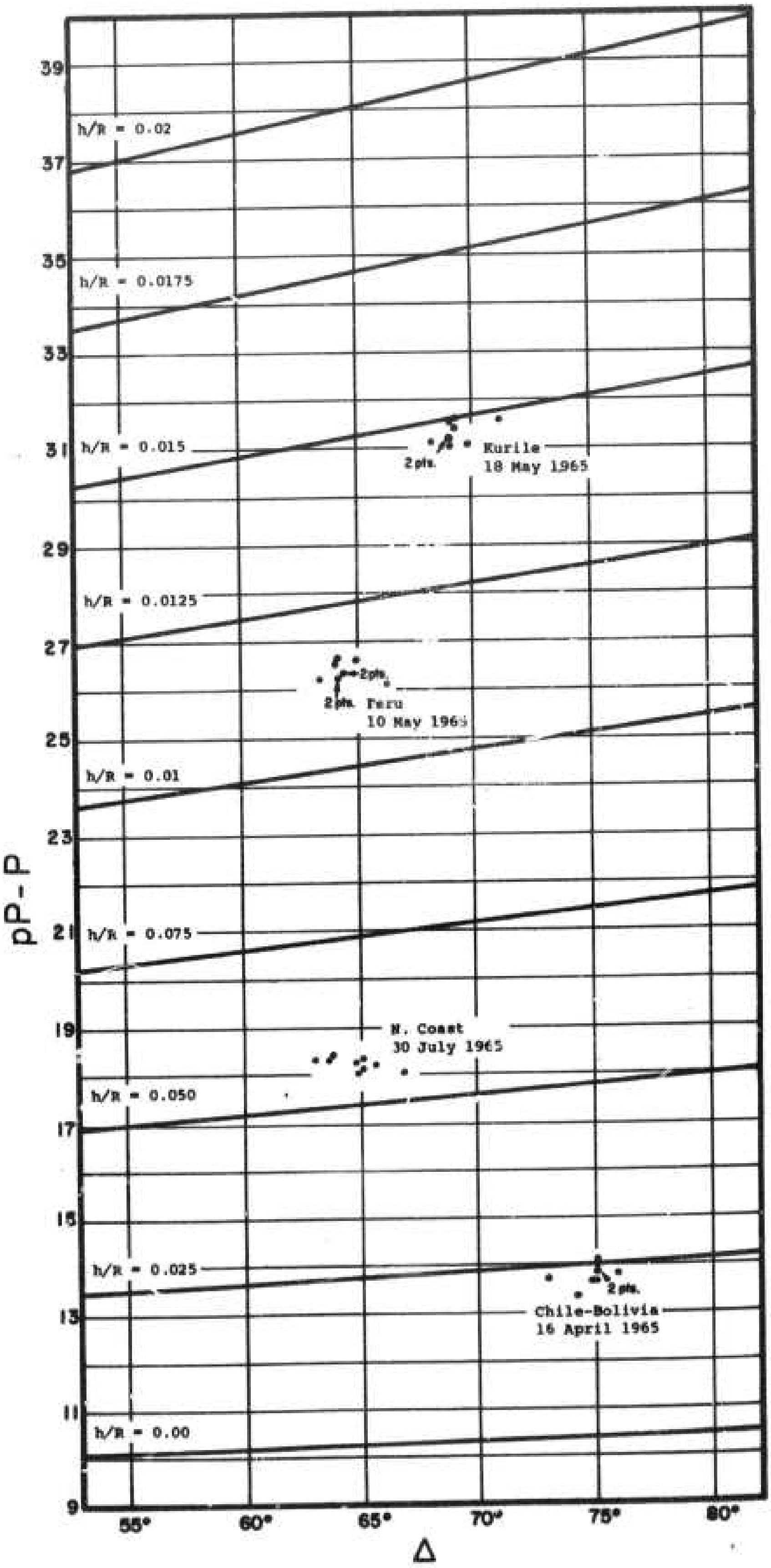
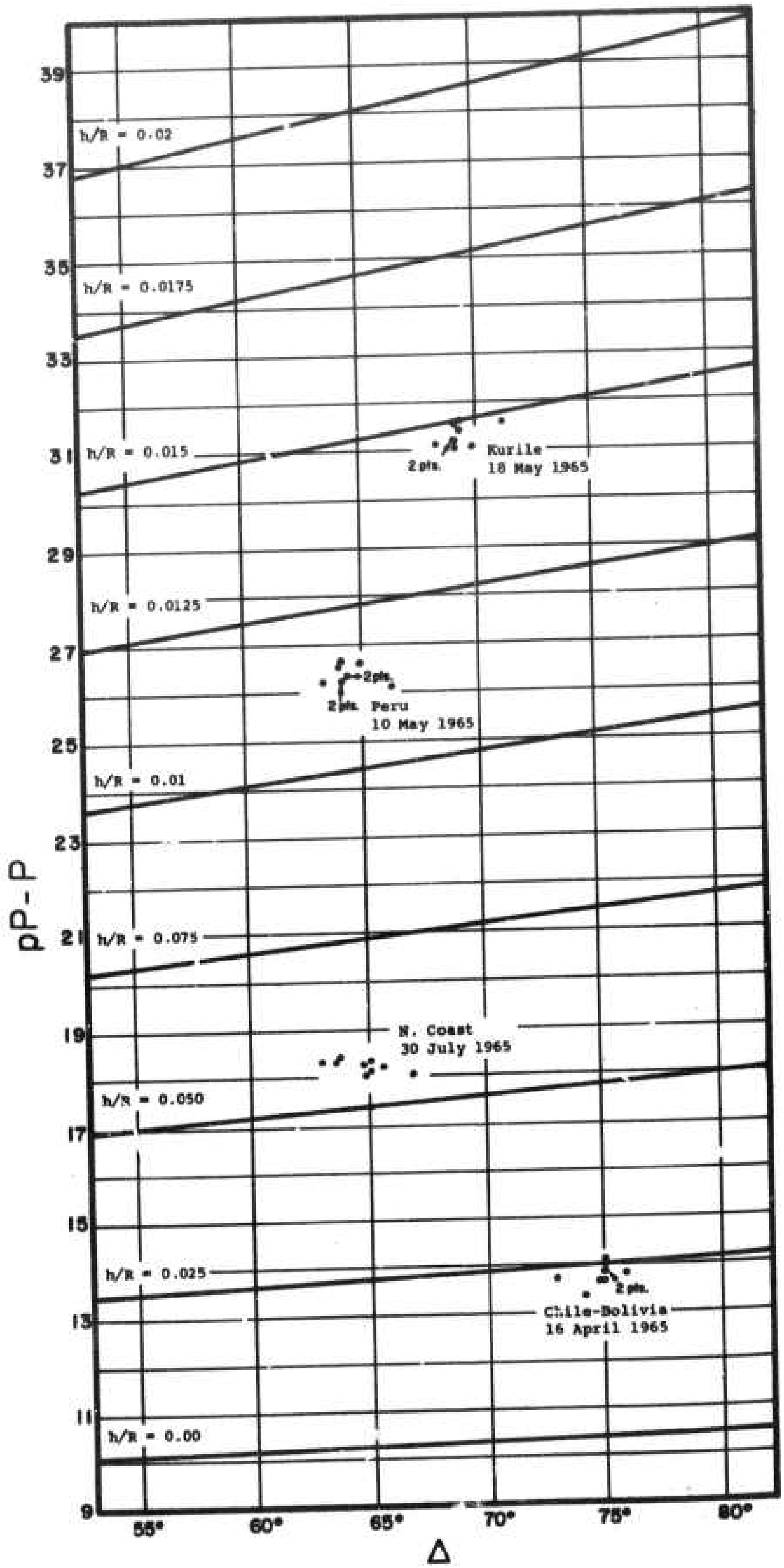


Figure 1. (pP-P) - Times



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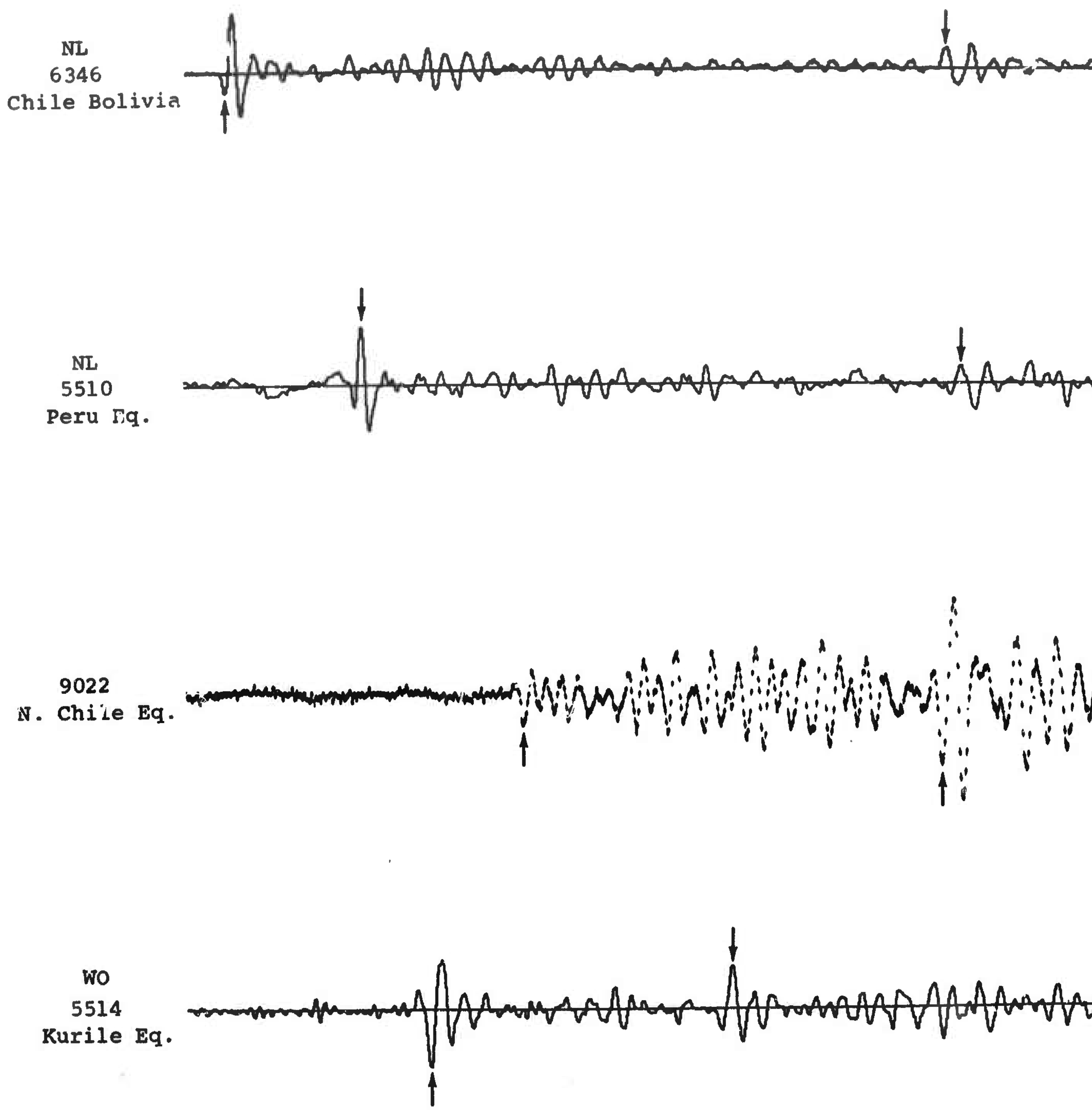

Figure 2. Examples of Seismograms Used

Station & Seismogram Number	P	pP	(pP-P)
SG 5511	2257 58.8	2258 12.5	13.7
JR 6087	2258 06.9	2258 20.2	13.3
LG 6164	2258 09.7	2258 23.3	13.6
NL 5548	2258 10.6	2258 24.2	13.6
WO 5514	2258 11.0	2258 24.9	13.9
TFO 5513	2258 11.1	2258 24.9	13.8
SN	2258 10.0	2258 25.0	14.0
HR 5512	2258 11.8	2258 25.6	13.8
GE 5511	2258 15.7	2258 29.6	13.9

Table 1. Kurile Earthquake - 18 May 1965

Station and Seismogram Number	P	pP	sP	(pP-P)	(sP-P)
SG 9023	0556 05.2	0556 23.2	0556 23.2	18.0	27.2
JR 9027	0555 56.3	0556 14.5	0556 23.3	18.2	27.0
NL 9022	0555 51.9	0556 10.0	0556 19.1	18.1	27.2
LG 9024	0555 52.8	0556 11.1	0556 20.0	18.3	27.2
WO 9026	0555 50.6	0556 08.6	0556 17.6	18.0	27.0
TFO 9028	0555 51.1	0556 09.2	0556 18.2	18.1	27.1
HR 9021	0555 50.9	0556 09.3	0556 18.0	18.4	27.1
SN 9020	0555 50.6	0556 08.9	0556 17.7	18.3	27.1
GE 9025	0555 45.9	0556 04.2	0556 13.1	18.3	27.2

Table 2. North Coast Chile Earthquake - 30 July 1965

Station and Seismogram Number	P	pP	(pP-P)
SG 5363	0846 00.2	0846 26.4	26.2
JR 6074	0845 51.1	0846 17.7	26.6
NL 5510	0845 46.9	0846 13.2	26.3
LG 5363	0845 47.9	0846 14.2	26.3
WO 5370	0845 46.3	0846 12.5	26.2
TFO 5364	0845 46.1	0846 12.3	26.2
HR 5364	0845 45.9	0846 12.5	26.6
SN 5369	0845 45.5	0846 12.0	26.5
GE 5368	0845 40.7	0846 06.9	26.2

Table 3. Peru Earthquake - 10 May 1965

Station and Seismogram Number	P	pP	(pP-P)
SG 6348	1302 58.4	(1303 30.0)	(31.6)
JR 6350	1302 50.2	(1303 21.4)	(31.2)
NL 6346	1302 46.2	1303 17.6	31.4
LG 6343	1302 46.5	1303 18.1	31.6
WO 6345	1302 45.3	1303 16.8	31.5
HR 6344	1302 45.3	1303 16.4	31.1
TFO 6342	1302 45.3	1303 16.5	31.2
SN 6347	1302 44.4	1303 15.6	31.2
GE 6349	1302 40.2	1303 11.3	31.1

Table 4. Chile-Bolivia Earthquake - 16 April 1965

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